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A LUNAR LABORATORY

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ABSTRACT

An international research laboratory can be established on the Moon in the early years of the 21st Century. It can be built using the transportation system now envisioned by NASA, which includes a space station for Earth orbital logistics and orbital transfer vehicles for Earth-Moon transportation. A scientific laboratory on the Moon would permit extended surface and subsurface geological exploration; long-duration experiments defining the lunar environment and its modification by surface activity; new classes of observations in astronomy; space plasma and fundamental physics experiments; and lunar resource development. The discovery of a lunar source for propellants may reduce the cost of constructing large permanent facilities in space and enhance other space programs such as Mars exploration.

INTRODUCTION

Over the past few years the authors have organized and attended a number of studies, workshops, and symposia addressing possibilities for future manned space exploration programs. Among the conferences are included the Lunar Bases Workshop /1/, the Lunar Bases Symposium /2/, and the Manned Mars Missions Study /3/, all of which promoted deliberations and formed conclusions on extraterrestrial bases and outposts. We have focussed recently on manned explorations to supplement current experience in unmanned investigations in the hope that an optimum mix of manned vs. unmanned scientific capabilities will emerge. The purpose of this paper is to show how a manned research laboratory on the Moon offers unique opportunities for geological and astronomical observations, as well as for certain kinds of fundamental physics experiments.

A LUNAR BASE IN PERSPECTIVE

Very recently, the United States' National Commission on Space, chaired by Thomas O. Paine, published its report/4/ on future space endeavors. That report takes the view that a nation can best determine which space programs should be developed over the next 20 years by looking ahead 50 years and deciding where it wants to be then. We take that view here in order to put the lunar laboratory in perspective.

Supporting Transportation Systems

We assume that the lunar research facility will be built within a broadly based infrastructure of stations, vehicles, and programs that can be developed in an evolutionary space program /5/. The first element of the infrastructure is the reusable space shuttle and its subsequent derivatives necessary for transportation between the Earth's surface and the space station. The next element is the low-Earth-orbit (LEO) space station, which will serve as a transportation node, or spaceport, to support further ventures deeper into space. The third element will include orbital transfer vehicles for hauling cargoes and people between LEO and geosynchronous orbit, low-lunar-orbit, or other spaceports that may be located at particular libration points /6/. Given that much infrastructure in place, a nation could establish and maintain a lunar outpost with relative ease after developing an appropriate lunar lander.

Figure 1 suggests a supportive role that a lunar base might play in a space program several decades into the future. The curves indicate the changes in velocity (delta-v) that are required for a rocket to travel from one place to another. As the rocket equation shows /6/, the larger delta-v is, the larger will be the mass of propellant required for the trip. The surface of the Earth is depicted in Fig. 1 as being at the bottom of a deep "well." The largest single delta-v step shown is that of lifting an object from the surface of the Earth to LEO. Clearly, this step must be performed as efficiently as possible and will eventually involve new innovations such as aerospace planes and shuttle-derived heavy lift launch vehicles. Furthermore, the sooner extraterrestrial resources can be used in an expanding space program, the less dependent the program will be on this expensive first step and the faster it can grow. The Moon has abundant resources.

Lunar Resources

One of the easiest things to get from the Moon is soil, or regolith, for radiation shielding at a habitat that is located either on the lunar surface or, for instance, at some spaceport placed far from the Earth and Moon. Lifting an object from the Moon requires a delta-v of only 2.4 km/s, whereas lifting it from the Earth requires a total delta-v of over 11.2 km/s. Beyond the protection of the Earth's magnetic field, an annual biological dose from galactic cosmic rays is about 50 rem /7/; 5 rem per year is allowed for radiation workers in the United States. In addition, several solar flares per 11-year Sun spot cycle could be lethal to astronauts without a radiation "storm cellar" of some type. If lunar regolith were used for shielding, the cost of lifting inert material from the surface of the Earth would be avoided.

Oxygen will be important to a growing space program. Forty percent of the Moon is oxygen--locked up tightly in chemical bonds. However, many ways of extracting oxygen from lunar regolith have been studied, and several appear to be feasible /8/. This suggests that hydrogen, the lighter element of hydrogen- oxygen propellant for rocket engines, can be brought up from Earth and that oxygen, the heavier element, can be manufactured on the Moon. Figure 2 relates the development of a lunar base to the growth of lunar resource support of the transportation system. Initially, the base is totally dependent on terrestrial supply, which means that 7 kg of propellant is needed in LEO to place 1 kg on the lunar surface. With the introduction of lunar oxygen, first into near-Moon operations and then into the return path to Earth, the slope of the curve changes from 7:1 to 3.5:1. As manufacturing capabilities increase to the point at which aerobrakes (heat shields for vehicles decelerating in a planet's atmosphere) can be manufactured from lunar materials, the slope decreases to something slightly greater than 1:1.

As the base becomes self-sufficient, only trace minerals and crew changes are charged to lunar operations, and the slope of the curve in Fig. 2 is essentially flat. In time, there could be economic balance between the Earth and the Moon. Lunar "credits" are shown quantitatively in Fig. 2 at the point where a closed ecological life support system (CELSS) is established after significant manufacturing capabilities are available.

Another potential lunar resource is glass. Lunar glass may possess higher tensile strength than that of equivalent materials on Earth. The strength of silicates is reduced by an order of magnitude on Earth because of the hydrolysis of Si–O bonds at crack tips or dislocations. In the extremely anhydrous environment on the Moon, hydrolytic weakening will be suppressed /9/. Thus, lunar silicate glass could possibly be substituted for structural metals in a variety of space engineering applications.

Still other commodities useful to an expanding space program could be produced on the Moon. Metals, such as iron or titanium, can be extracted from the lunar soil, rocks, or minerals with differing degrees of difficulty. For example, small quantities of metal (primarily iron) from meteorites can be concentrated with a magnetic device from large amounts of lunar soil; or, with much larger energy inputs, titanium can be obtained from ilmenite. These products could be used in large space structures. Lunar titania or alumina might be used to produce aerobrakes for returning to Earth or landing at Mars. At higher levels of development, the production of components for solar electric power generation in space (e.g., solar power satellites) could be feasible /10/.

Complementary Resources from Mars

Water is known to exist on the surface of Mars /11/. However, to avoid having to use the propellant required to remove resources from Mars, where the escape velocity is 5 km/s, one may first seek resources at Mars' moons, since only docking maneuvers are needed to approach them. There is strong evidence that Mars' two moons, Phobos and Deimos, have compositions similar to that of a carbonaceous chrondrite--a type of meteorite that is rich in water and organics /12/. Furthermore, returning to Fig. 1 we see that the delta-v required for a 3-day trip from LEO to a soft landing on the Moon is approximately the same as the delta-v required for an 8-month trip from LEO to Deimos. If unmanned freighters are used to carry cargoes from Mars' vicinity to Earth's vicinity, the long trip time could be tolerated. So we may find that the resources of the Moon, which are quite dry and contain only traces of carbon, and those of Mars' moons will complement the needs of a growing space program.

Costs

Costs of placing on the Moon a permanent base housing 24 people were estimated in 1968 by a Stanford-Ames study /13/. The group concluded that over a 15-year period, the total development, acquisition, delivery, and building costs would be $17 billion, which translates to $60 billion in 1986 (1 billion = 10^9). This figure is consistent with a recent NASA assessment showing that a permanent lunar base, and the necessary orbital transfer vehicles and lunar landers, can be built over 25 years for about $90 billion in 1986 dollars /14/. To compare, the Apollo program that landed a dozen astronauts on the surface of the Moon was completed in 11 years and cost about $88 billion in 1986 dollars.

The Apollo program developed when the U.S. gross national product was less than one-half of what it is today, after accounting for inflation /15/. Thus, if a lunar base project were built by the U.S. over about 2 decades, it would have less than one-fourth as much annual impact on the U.S. economy as did the Apollo program during the 1960s. Putting it differently, a permanent lunar base can be built for less than one-tenth of one percent of the cumulative U.S. gross national product./15,16/. However, although the U.S. can afford to build a permanent base on the Moon without the help of other nations, that may not be the most desirable way to go about it.

International Cooperation

A lunar laboratory could serve as a vehicle for future international cooperation by coordinating tasks to take maximum advantage of the complementary technological skills of all participating national space programs. In this way, cooperation among nations will be encouraged by large scientific programs as was done, for example, in the International Geophysical Year efforts in 1958.

The international nature of this project must be studied carefully. Two models are suggested by analogy with the CERN and Fermilab particle accelerator laboratories. CERN (Geneva) was built by--and is managed by representatives from-- several countries: Fermilab (Chicago) was built and is managed by one country. Both laboratories are "international" and have accepted research scientists from all over the world. We are not prepared to suggest a specific model at this time, but the idea is not without precedence. Spacelab is an international laboratory built by the European Space Agency and launched into LEO on the U.S. shuttle. An international research laboratory on the moon may be merely a logical extension of Spacelab.

Science as a Rationale?

We agree with the viewpoint expressed by the National Commission on Space when it reports, "The Solar System is our extended home.... Now space technology has freed humankind to move outward from Earth as a species destined to expand to other worlds" /17/. This viewpoint suggests that the scientific exploration of space has a special meaning for scientists and non-scientists alike --a meaning that transcends the usual rationale for doing science. With this viewpoint in mind, we can accept the premise that science alone may not be a sufficient reason for spending money to explore space or build a lunar laboratory, and still we can presume that someday a lunar base will be justified and built. It will be built for many reasons, including perceived scientific, political, and economic benefits.

So the key question to be answered by the scientist is, "Given that a lunar base will be established, what are interesting and unique scientific investigations that people can do on the Moon?" It is from the broad perspective outlined above, showing how a lunar base fits into the context of an larger expanding space program, that we turn to this question.

SCIENCE AT A MANNED LUNAR LABORATORY

The Moon is a cornerstone for comparative planetology because it evolved without atmosphere or water, and records of early geological events still can be found. A permanent lunar base offers the opportunity to study the Moon in much greater detail than has ever been possible. It also allows us to use the unique lunar environment as a platform for astronomical, solar, space plasma, and fundamental physics experiments.

The Lunar Environment

The lunar environment is characterized by low gravity (one-sixth that of Earth), high vacuum (2×10^5 molecules/cm^3, or 10^{-12} torr), seismic stability (10^{-8} times the seismic energy of Earth), low temperatures at the poles (about 70 K), large diurnal temperatures at the equator (100 to 385 K), and low radio noise on the far side. A few meters above the surface on the dayside, there is an electric field of roughly 20 volts/meter resulting from photoelectric interactions of sunlight on the regolith. The Moon spends three-fourths of its time in the solar wind and one-fourth of its time in the

Earth's geomagnetic tail. Magnetic fields vary across the Moon's surface from about 30 to 300 gammas (1 gamma = 10^{-5} Oersted = 10^{-5} Gauss). The tenuous lunar atmosphere consists of solar wind gasses (mostly hydrogen, helium, and neon) and minor amounts of other gases apparently outgassed from the lunar interior. The entire lunar atmosphere has a mass of about 10^4 kg. Since there is practically no atmosphere to produce decaying pions from cosmic ray interactions, calculations show that, for neutrino energies between 1 Gev and 1 Tev, the neutrino background is 100 times lower on the Moon than on the Earth /18/. Primary cosmic ray intensities are more uniform and constant than at the Earth. Solar flare protons at high flux levels represent the most hazardous short-term radiation problem for human beings. A regolith 2 to 30 meters thick covers the entire lunar surface, having a density that increases from 1 to 1.8 gm/cm^3 as the depth increases from 1 mm to 20 cm. The Moon turns slowly, giving 2-week days and nights, and large thermal gradients are produced between shadow and sunlight. Micrometeorites at cosmic velocities bombard the surface of the Moon at a rate of $300/m^2/yr$, making craters 10 micrometers in diameter /19/.

Lunar Science

Traces of the key events in solar system history have been abolished on Earth by vigorous terrestrial geologic processes. To understand the Earth's early history, we must study the Moon. Even with the wealth of knowledge gained about the Moon by the Apollo Program, there are still many unanswered questions. We do not know, for example, how the Moon formed or evolved, nor do we know the composition and structure of the crust and mantle. What is the size of the metal core, if there is one? What is the thermal history of the Moon, and what is the nature of lunar volcanism? We do not know the history and nature of the impact processes of the Moon. An elaborate network of in-situ measurements must be made before these questions can be answered confidently.

An array of about 30 seismic detectors should be distributed uniformly over the surface of the Moon to characterize the lunar interior more effectively. This network must operate continuously for many years to detect and analyze naturally occurring moonquakes and to record the travel times of the stress waves initiated by large meteorite impacts. Heat flow measurements should be made at many sites so that the amount and distribution of radioactive elements within the Moon can be determined. This information is crucial to models of lunar structure, bulk composition, and history.

A lunar base can provide the opportunity for detailed studies of lunar samples collected from all types of terrain. These investigations can determine the ages of the oldest and youngest rocks, the style of emplacements of the earliest crustal units, the nature of rocks brought up from depths by large impacts, and the manner in which material is hurled across the surface by those impacts. These examinations require that the lunar surface be mapped and sampled along traverses hundreds of kilometers long and that crater walls and central uplifts be scaled. These studies are needed to develop a full understanding of the origin and evolution of the Moon's crust.

The rocks and soil exposed at the lunar surface are greatly depleted in volatiles ~~tiles~~ compared with those of Earth, which implies that their source materials passed through an extensive outgassing stage. However, high concentrations of some volatile elements are found deposited on the surfaces of glass droplets formed during volcanic explosions and collected at the Apollo-11, -15, and -17 sites. These data indicate that some volatiles are present in the lunar interior and may be carried to the surface by volcanic eruptions. In addition to the desirability of finding water in the Moon, finding small quantities of other volatiles there will have major implications for our understanding of lunar origin, composition, structure, and history.

Finally, the Moon is a useful detector that can give valuable information about solar and cosmic-ray history. The core samples obtained during the Apollo missions contain a record of the Sun's history, but the lunar regolith is too complicated to be understood on the basis of a few samples. Detailed studies supported by a lunar base would include coring up to 10 m deep, trenching, in-situ appraisal of lunar regolith sections, and numerous inspection sites and analyses.

Astronomy from the Moon

There are significant scientific questions that can be answered only with astronomical observatories having higher angular resolution and greater sensitivity than is possible at facilities on the Earth. The current model for the central energy source in galactic nuclei and quasars involves a black hole accreting mass from surrounding stars; tests of this model require micro-arcsec resolution at radio, optical, and x-ray wavelengths. The detection of planets orbiting nearby stars, fundamental improvements in the cosmic distance scale, and more precise estimates of the "invisible" mass in the universe call for ultrahigh resolution at optical, infrared, and radio frequencies. Detailed observations of primordial galaxies with large red-shifts in the optical, infrared, microwave, and x-ray wavelengths will provide information on the evolution of galaxies and the universe. Comets residing in the inner part of the Oort cloud, 1,000 to 100,000 astronomical units away, could be detected and studied with a 30-m-aperture optical telescope. The versatile facilities needed to make these fundamental investigations can be located at a lunar base.

In some respects, the Moon is an ideal place for an astronomical observatory. A lunar observatory will have no atmospheric absorption and will provide a stable and seismically quiet platform, natural access to cryogenic temperatures, and low gravity for building large signal-collecting areas. In the lunar environment, "naked" detectors may be operated. Arecibo-type radio antennas may be contoured within existing craters, and long baseline interferometers may be established. The far side of the Moon is always shielded from the Earth's electromagnetic noise. Full darkness lasts for 14 days. The slow rotation rate of the Moon makes it a simple task to track a celestial object from a lunar platform. For these reasons, astronomical measurements on the Moon will result in higher angular resolution and greater sensitivity than those made at comparable facilities on the Earth and, in some cases, in LEO /20,21/.

The sensitivity for telescopes varies as the effective area of the aperture; the angular resolution for telescopes is l/D, where l is the electromagnetic wavelength, D is the aperture diameter, and the resolution is given in radians. Thus, for visible light with l = 500 nm, a 1-m-diameter telescope will have an angular resolution of 0.5 micro-radians, or 0.1 arcsec. However, 0.1 arcsec resolution cannot be obtained on Earth because of atmospheric disturbances, and the Hubble Space Telescope Program will place a 2-m telescope into LEO with the space shuttle so that the ideal resolution can be achieved.

Putting larger optical telescopes into space is a subject already being discussed and at some point, rather that building them on Earth and launching them into space, it will be more ecomomical to build telescopes with indigenous lunar materials and anchor them firmly on the lunar surface. A 30-m mirror would deform under its own weight, even on the Moon, so a segmented mirror would offer the largest optimum field of view. For thermal protection, the telescope could be housed inside a dome." Such a telescope can work in the electromagnetic spectrum from ultraviolet wavelengths to mid-infrared wavelenghts--limited by mirror coatings and polish at smaller wavelengths and by thermal mirror emissivity at the larger wavelengths /22/. Also, very large arrays (VLAs) of optical telescopes can be designed using interferometry techniques to synthesize an effective aperture, which is the largest dimension of the array. The feasibility of an optical VLA with 27 individual 1-m telescopes has been investigated /23/. These dimensions suggest an angular resolution of 10 micro-arcsec for visible light. This resolution is sufficient to view sunspots on other stars and extragalactic processes as they are manifest in quasars and galactic nuclei. To achieve this resolution, phase stability requires 25 nm tolerances and adequate thermal protection probably requires large structures to cast shadows over the telescope. These requirements appear to be achievable on the lunar surface.

The 3 milli-arcsec resolution of Earth-based radio astrometry is limited in a fundamental way by the 7 ns variable delay caused in the troposphere and by cm-scale motions of the Earth. By placing radio telescopes on the Moon, the troposphere delay problem can be eliminated and the baseline shifts can be greatly reduced. Operating the telescope above the 20 GHz range will probably eliminate delay effects due to the Moon's ionosphere, which must otherwise be taken into account. Resolution in the 0.1 to 1.0 milli-arcsec regime should be achievable /24/. This would make it possible, for example, to measure the Sun's proper motion about the galactic center with a 2% accuracy in 1 yr.

For the past several decades, radio astronomers have been enhancing resolution using interferometry, and those efforts have culminated in the concept of aperture synthesis. Radio VLAs already exist on the plains of St. Augustine mear Socorro, New Mexico, U.S.A. A Y-shaped array of 27 atennas, each arm being 20 km long, operates as a coherent array, giving 0.1 arcsec resolution at 2 cm wavelength. Furthermore, very long baseline inteferometry (VLBI) has been conducted on Earth, the limit being the diameter of the Earth. The possibility of using combined space-based and lunar-based systems to take full advantage of the Earth-Moon baseline, has been examined /25,26/. The Moon-Earth Radio Interferometry (MERI) system would operate in the 30 MHz to 300 GHz frequency range, giving a resolution of 13 micro-arcsec at 10 Ghz and 0.4 micro-arcsec at 300 Ghz. Hence, a few meter resolution could be obtained by viewing Mercury, 5 x 10^5 km resolution at Orion Nebula, and 0.1 astronomical unit resolution at the galactic center.

And finally, it has been pointed out that because the Moon's spin axis is ~~included~~ clined only $1^1/_2$ degrees from the normal to the plane of the ecliptic, there are regions near the poles in permanent shadow /2~~7~~8/. These very cold regions offer a natural, low-noise environment for astronomical observatories.

SCIENCE IN SPACE

We have described one class of scientific investigations that can be conducted on the Moon as "science in space," (science conducted under various conditions extant in space) which is to be distinguished from space science (the science of the phenomena of space) /29/. Most basic experiments focus on reducing systemmatic errors by changing critical parameters, but we seldom consider the Earth's gravitational acceleration, for example, as a variable in experiments. Science in space is a class of investigations that can benefit from changing some of the most fundamental parameters of the Earth's environment.

New levels of chemical purity, low magnetic fields, low neutrino backgrounds, and direct access to large-volume high vacuum suggest exciting discoveries in fundamental science. For example, it will be important to investigate the biological consequences of low magnetic fields. Furthermore, new frontiers in materials science can be advanced in the clean conditions, low gravitational fields, and abundant solar energy available at a lunar research laboratory.

As one further illustration of science in space, we mention a fundamental physics experiment that requires very low magnetic fields over a volume of many m^3. An electric dipole moment (EDM) for any particle implies a nonuniform charge distribution. The conservation of parity and time reversal invariance (TRI) each require that the EDM for all particles must vanish. But grand unified theories predict an EDM for the neutron so that the discovery of a neutron EDM would have broad implications fo present thinking on theories of matter.

Experiments show that the neutron EDM is smaller than 10^{-25} e-cm (EDM is measured in units of electron charge, e, and distance, cm), and the sensitivity may ultimately reach 10^{-27} e-cm on Earth. However, a sensitivity near 10^{-28} e-cm would be necessary to make definitive statements about the cause of TRI in nature, and a null result would be important. EDM experiments use nuclear magnetic resonance techniques with the neutron magnetic moment precessing around weak magnetic fields. A 10^{-28} e-cm measurement requires exclusion of extraneous magnetic fields to the 10^{-9} G level. For a practical NMR apparatus, this may not be possible on the Earth, even with a superconducing shield. On the Moon, however, starting with a 10^{-4} G field and an easily obtainable 10^{5} shielding factor using standard methods, 10^{-9}G should be possible /29/. Thus, a permanent lunar research laboratory, if it already existed for other reasons, could be used for conducting critical experiments to learn more about the nature of matter.

CONCLUSIONS

We have started from the perspective that the next several decades will see a growing interest and capability in space exploration. As a consequence, we believe that a lunar base will be established in the not too distant future for a variety of reasons, including anticipated scientific, political, and economic benefits. Because of the long lead times for large space projects and experiments, it is not too early to contemplate what types of scientific activities should be undertaken at a manned base on the Moon. Doing so puts us in a better position to influence, as scientists, how a lunar base will evolve.

Research investigations at a lunar laboratory can be placed in three categories: Lunar Science, Astronomy, and Science in Space. We have discussed unique experiments that can be conducted at the Moon in each of these categories. Our discussion has focused on examples, and was not intended to be an exhaustive list of scientific opportunities at a lunar laboratory. We hope we have chosen examples that will stimulate the interests of scientists from other nations so that the future of manned exploration in space will be truly an international cooperative effort.

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